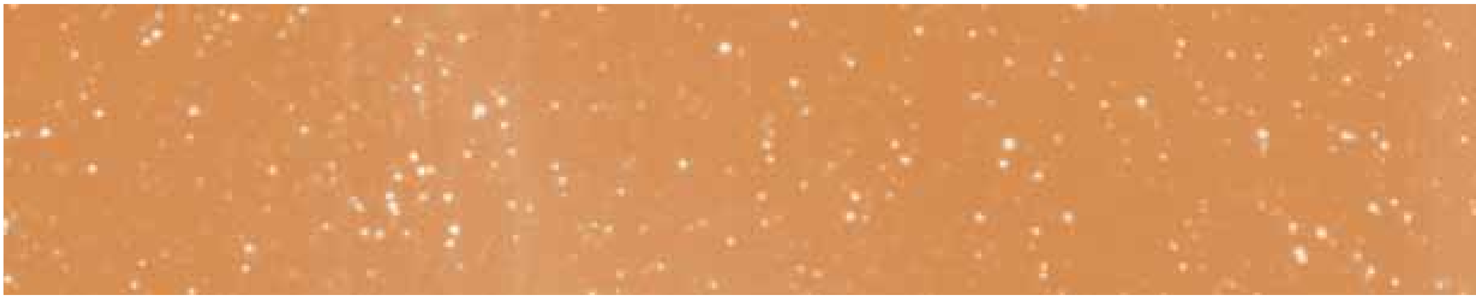


PART II
The Department of CELESTIAL MAGNETISM

by VIRGINIA TRIMBLE

The larger the magnetic field, the stronger our ignorance.

—Virginia Trimble (30 years after Nordwijk)

PART I EXPLORED PLANETS AND STARS, whose magnetic fields are moderately well understood, but not energetically important. In Part II, we* move on to interstellar, galactic, intergalactic, and cosmic magnetism, sites where the fields are energetically and dynamically much more important, but a good deal less well understood.

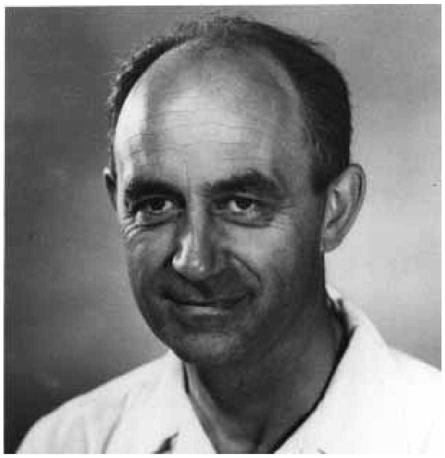
BEGINNINGS

Among the good things to come out of World War II was an enormous boost to radio astronomy, in the form of left-over radar dishes and people with the vision to point them up rather than sideways. This included John Hey, Martin Ryle, and Bernard Lovell in England and Bernard Mills and John Bolton in Australia. They had a meager foundation to build on—the recognition by Karl Jansky in about 1935 that the disk and center of our galaxy were a major source of noise interfering with trans-Atlantic radio

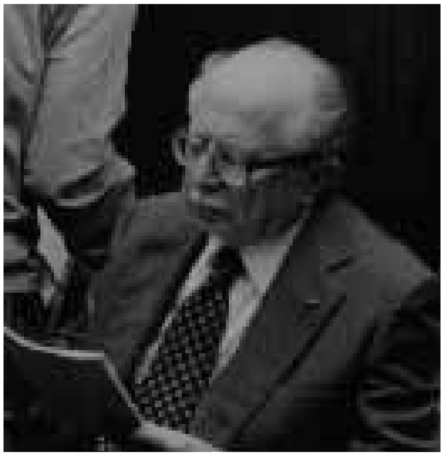
---

*Or in any case I; but please do come along if you don't have aything else that absolutely has to be done in the next 20 minutes or so.

Hannes Alfven. Early enthusiast for a large-scale galactic magnetic field and galactic cosmic rays. Alfven waves (magnetohydrodynamic or MHD) constitute an important solution of Maxwell's equations not discovered by Maxwell.



Enrico Fermi. Perhaps the last person of whom one could say simply "physicist," meaning both theory and experiment on many topics. His mechanism for accelerating and confining cosmic rays requires a galactic magnetic field.



Jesse Greenstein. Among the first optical astronomers to take radio astronomy seriously and co-proposer of a mechanism for aligning interstellar grains so that they will polarize passing starlight. He was my first co-author (on white dwarfs, but not magnetic ones).

telephony (he worked, of course, for Bell Labs) and by Grote Reber in 1944 that the sun is the brightest thing around at any wavelength (he was the quintessential backyard astronomer, having built his own radio reflector with which he also found radio emission in the direction of Cygnus).

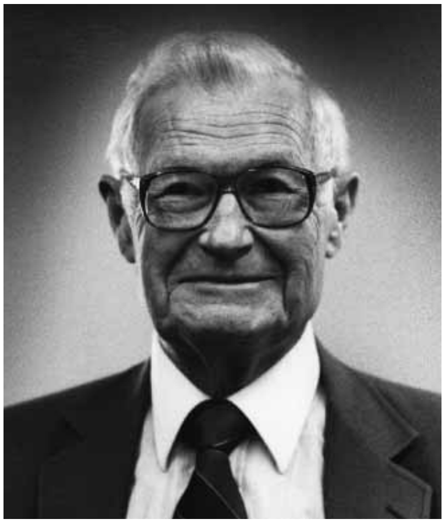
The post-war heroes, struggling with high noise and low angular resolution, succeeded in demonstrating the existence of compact sources, including the already notable Crab Nebula (remnant of a supernova seen in 1054), but also others that didn't seem to be any particular interesting place at all, like Reber's Cygnus A.

The main stream (optical) astronomical community reacted with profound apathy, even when Reber, and soon after Jesse Greenstein, showed conclusively that known emission processes failed by orders of magnitude to account for what was being seen. At one point, the editor of the *Astrophysical Journal* thought it necessary to print an editorial assuring potential authors that papers in radio astronomy were not automatically rejected. He was not entirely believed.

Meanwhile, things were stirring on two other fronts. First, Hannes Alfven and Enrico Fermi had been worrying about how to confine cosmic rays within the Milky Way and how to shove them up to relativistic energies in the first place. They concurred in 1949 papers that a large-scale galactic magnetic field of about 10 μG would be useful in both contexts. It is conceivable that this is the last (and first?) time that Alfven agreed with anyone, but further research is needed on the point.

Second, back at the traditional optical ranch, John Hall and William Hiltner had gone out to look for polarization of starlight that, according to Chandrasekhar, should result from electron scattering of radiation in the atmospheres of hot (blue) stars. In 1949 they reported success of a sort, in separate papers (the collaboration by then having fallen apart, never to be reassembled—magnetic fields seem to have that effect on people). The light of many blue stars was indeed linearly polarized at the 1–3 percent level. But a map of polarization angles over the sky showed large-scale structure, mostly parallel to the plane of the Milky Way, with some loops and

John Hall. Co-discoverer of interstellar polarization. He and Hiltner died within about a month of each other in fall 1991.



William Hiltner. Co-discoverer of interstellar polarization (in his days at the University of Michigan).

Josef Shklovsky (right) and Harold Zirin. Shklovsky was an early proponent of the synchrotron mechanism to account for continuum radiation from supernova remnants and active galaxies. Zirin, a expert observer of solar magnetic activity, translated and edited Shklovsky's memoires with his wife Mary.

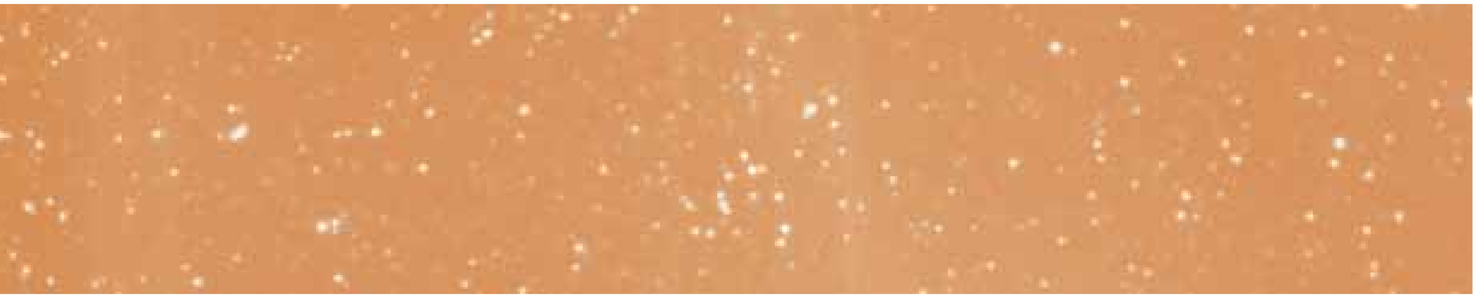
wiggles, which made no sense as an effect of processes in the stars themselves.

The three fronts began to converge in the early 1950s. First, Alfven and Herlofson said that synchrotron radiation (emitted by relativistic electrons spiraling in magnetic fields) was the key to understanding radio waves from the discrete sources. In the very next, also 1950, volume of *Physical Review*, Karl Kiepenheuer proposed the same mechanism for diffuse galactic emission. Ludwig Biermann imagined that such a field might be in equilibrium with galactic turbulent gas motions, and so have a strength of about 10 μG.

Next, Leveritt Davis, Jr. and Jesse Leonard Greenstein proposed that the Hall-Hiltner polarization was light scattered by dust grains that had been lined up in a large-scale galactic magnetic field. The mechanism they proposed may or may not be the dominant one—it depends on the shapes of the grains and what they are made of. But their explanation of the polarization of starlight is now always advertised as the discovery of the galactic field. Jesse has said that he had magnetism on the brain at the time because of having heard Fermi talk about the cosmic-ray problem at Chicago, thus tying directly to the third, theoretical, front.

Josef Samuelevich Shklovsky (his spelling, but authority has preferred Iosef, Shklovskii, and Shklovskij) pushed synchrotron emission upward to visible wavelengths for the Crab Nebula, predicting optical polarization of lots more than 1–3 percent, which his fellow countryman V. A. Dombrovsky (similar choice of spellings) found in the next year, 1954. The polarization of the Crab radio radiation turned up in 1959 in data collected by D. Kuz'min and V. A. Udal'tov (though many casual histories mention only a later American paper). And pretty soon the sky was filled with galactic and extragalactic polarized sources of synchrotron radiation.

Polarization of the diffuse galactic radio emission was firmly established (after much hard looking) in 1962 work by Gart Westerhout and Richard Wielebinski (each with several colleagues, named, of course, al.). The modern era can reasonably be said to begin with the 1968 discovery by Gerrit Verschuur of Zeeman broadening of the 21 cm emission from neutral gaseous hydrogen. Astronomers could then measure magnetic field strengths



and their place-to-place variations with some confidence. And it is doubly the beginning of the modern era for me and everybody else who received a PhD in 1968 (just as the line between history and "current events" is the year you started reading newspapers for yourself).

LOCAL INTERSTELLAR FIELDS AND THE PROBLEM OF STAR FORMATION

Stars form when already-dense clumps of interstellar gas collapse further. They don't find it easy. The overall rotation of our galaxy means that any region containing one solar mass of gas has far too much angular momentum to become a one solar mass star rotating at less than break-up speed. Magnetic fields would seem to make things worse. Here, after all, is yet another source of pressure for gravity to overcome, in addition to $P = nkT$, cosmic rays, random turbulent motions, and the excess angular momentum.

It greatly reduces the effort of remembering how big all these things are that the energy density (or pressure) in magnetic field, cosmic rays, turbulent motion, and thermal kinetic energy are all about the same through much of the interstellar medium—about 1 eV per cubic centimeter. This is arguably not a coincidence, but rather the result of cosmic rays tugging on field lines tugging on clouds which collide and heat each other and tug on field lines which confine cosmic rays which . . . I have never been sure whether it is a coincidence that the energy density of starlight near us is also about 1 eV/cm^3. The present 2.7K cosmic microwave background radiation also contributes a bit less than 1 eV/cm^3, everywhere, which is surely a coincidence. Isn't it??

In any case, Zeeman measurements confirm that condensing clouds have taken some of the average galactic field with them and have B = 10–30 μG, vs. 1–3 μG in more diffuse regions. And you might reasonably think this would make the star formation problem that much worse.

It doesn't. In fact, angular momentum and magnetic flux help to shove each other out of star formation regions, protostellar clouds, and very young stars. To attempt to apportion credit for the ideas would be to invite electronic, paper, and perhaps real over-ripe tomatoes to be aimed at Irvine, College Park, and even Stanford. I will merely say that I have heard the problems and the solutions most persuasively expressed by Leon Mestel (retired, but very much on active duty at the University of Sussex) and Telemachos Ch. Mouschovias of the University of Illinois).* Now you can quarrel with my taste, but not with my perception of history!

Leon Mestel. One of the major contributors to the theory of cosmic magnetic fields and their influence on star formation and other processes. He also proposed, with Malvin Ruderman, the correct solution to a problem in cooling of white dwarfs—the carbon and oxygen nuclei eventually form a crystal lattice!

The relevant process is simple, really, or, rather simplified (though I hope not beyond recognition). On the one hand, the field imposes co-rotation on the outer regions of cloud, protostar, or young stellar object until bits spin off carrying away more than their fair share of angular momentum per unit mass (the solar wind really does this now). And, on the other hand, the rotation first amplifies trapped field and, in due course, contributes toward dynamo generation of more. Thus the entities with strongest field and fastest rotation spin down and excrete magnetic flux most efficiently, leaving new-born stars that are faster rotators with more high-field star spots than their older cousins, but not unreasonably so. I have forgotten, though you must not,

**Prof. Mestel's undergraduate lectures in electromagnetism in his Cambridge days were reputed to feature two jokes, in alternate years. One concerned the disapPoynting vector, and the other did not. Prof. Mouschovias is not widely known to be associated with any jokes at all.*

ambipolar diffusion, which allows field to cheat its way out.

Observations tell you immediately where I have oversimplified. We definitely see gas flowing away from protostars and young stellar objects, but it looks more like jets and streams than like equatorial disks. Thus you have to think of the field twisting and turning in disks and collimating jets, which then do, nevertheless, carry off both angular momentum and flux.

The fields considered here belong to the galaxy as a whole, and we are not required to account for their origins until the next section.

LARGE SCALE FIELDS IN THE MILKY WAY AND OTHER GALAXIES

Hall and Hiltner told us the direction of the average interstellar magnetic field and Verschuur something about its strength in particular clouds of neutral hydrogen. Synchrotron radiation provides information about average direction (from polarization angle), about total strength (from the brightness of the radiation, provided you know the density of relativistic electrons), and about the relative importance of ordered and chaotic field components (from the amount of polarization). Thus we* came to the end of the 1960s reasonably sure that the galactic field had roughly equal strength in ordered and random components and that the ordered field lines were parallel to the plane of the galactic disk. Some spurs and loops out of the plane, which show both in polarized starlight and in synchrotron maps, were blamed on nearly shell-shaped old supernova remnants, of which more shortly.

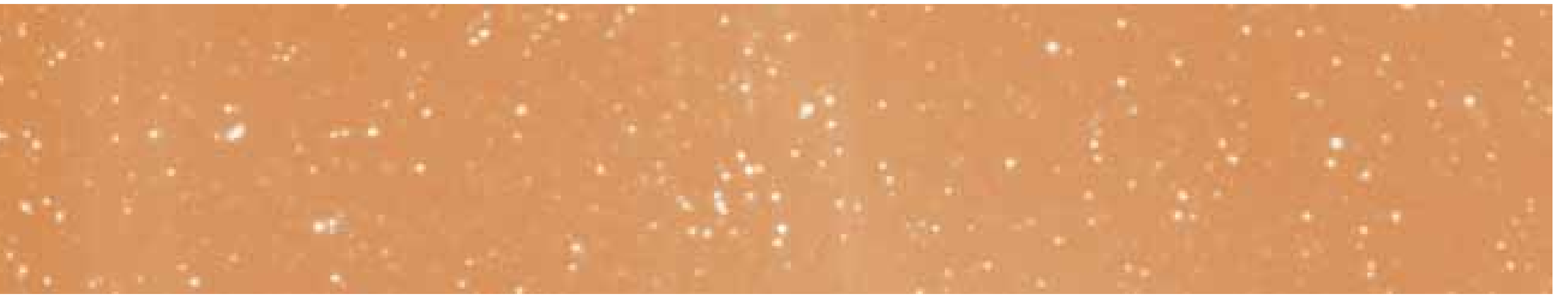
Starting in the mid 1960s, the best estimate of coherent field strength gradually shrank from 10–30 μG to 1–3 μG. The larger value would have made the field dominant over cosmic rays, turbulence, and such, so that it might have protected spiral arms from winding up in the differential rotation of our own and other spiral galaxies. This was what Woltjer had in mind at the Nordwijk symposium when he associated strong magnetic fields with ignorance. But, at the same time the field was shrinking, C. C. Lin of MIT and his students, especially Frank Shu, were looking at instabilities in differentially rotating disks and concluding that the arms are probably soliton-like waves. Current opinion endorses this sort of picture.

The discovery of pulsars in 1968 opened a whole new window on galactic magnetism, glazed with the effects called dispersion measure and rotation measure. Dispersion measure (DM) means that longer wavelengths take longer to get here through intervening plasma. The time delay is proportional to the integral of electron density, n_e, along the line of sight. Rotation measure (RM) means that the intrinsic plane of linear polarization is rotated through an angle, larger for longer wavelengths, that is proportional to the integral of $n_e B_{||}$ along the line of sight. Divide RM by DM, and you have the average field along the line of sight out to the distance of that particular pulsar. In addition, the 180 degree ambiguity in field direction as found from optical and synchrotron polarization disappears. Faraday rotation of synchrotron radiation from quasars and such outside the Milky Way provides $\int n_e B_{||} dl$ for the entire galaxy in different directions.

With more information, naturally the field pattern looks more complicated. The coherent part is still mostly in the galactic plane, with some concentration toward the spiral arms. The best bet on directions is that the field lines follow the arms rather than circles. Perhaps most interesting, the field direction reverses from being clockwise where we are to being counterclockwise both inside and outside the solar distance from the galactic center, and reverses back again at least once still closer to the center. (I haven't said whether you are looking from above or below the plane, and won't).

The simplest explanation is a two-armed spiral with field lines coming out of the galactic center along one arm and going in on the other, in what is called a bisymmetric spiral pattern (see figure on the next page). The

*"We" in this context means "a majority of the astronomical community." You will probably have noticed that "we" in these pieces more often means "author plus reader," or, occasionally, "author and Queen Victoria."



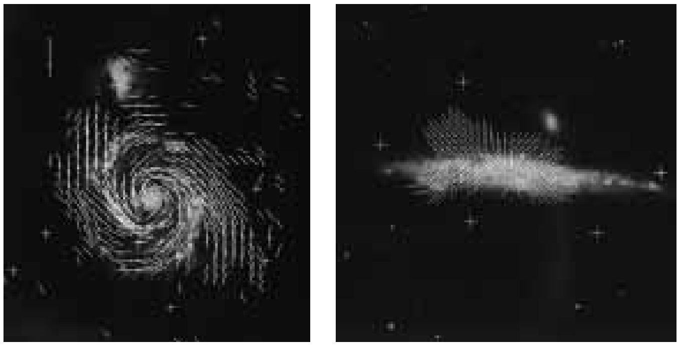
Left: Greatly idealized version of a slightly barred spiral galaxy (which ours is), with ordered, Grand Design spirals arms (which ours has not), and a bisymmetric magnetic field. This last may or may not apply to the Milky Way, but would at least account for the several reversals of prevailing field direction (colored arrows) seen as we look toward and away from the galactic center.

alternative is called an axisymmetric spiral, and has field either going out or coming in on both arms.

What about the galactic halo? Information is sparse, because there is little dust to be aligned, few stars to have their light polarized, little synchrotron emission (how much was once bitterly fought over as "the existence of the radio halo"), and few pulsars to be Faraday rotated. But the rising loops, chimneys, fountains, and champagne bubbles of hot, supernova-driven gas that penetrate into the halo must carry some field with them, and it ought to be roughly perpendicular to the disk.

The galactic center is a region of stronger magnetism, milli- rather than micro-Gauss, structured roughly like a dipole perpendicular to the plane, but with twists, filaments, and snakes that either trace or drive gas flows and distributions.

Other spiral galaxy fields are probably more or less like ours, although what you can measure varies. For face-on spirals, synchrotron polarization indicates field directions along arms and bisymmetry or axisymmetry perhaps correlated with whether the arms are tidy or messy (the technical terms are Grand Design and flocculent spirals). M51, shown below, is a classic Grand Design, two-armed spiral, with field directions along its arms. For edge-on ones, polarization necessarily tells us about fields perpendicular to the disk. My favorite is NGC 4631, shown below, with ought to be called the hedgehog galaxy. NGC 891, sometimes spoken of as a twin to the Milky Way, is rather similar.



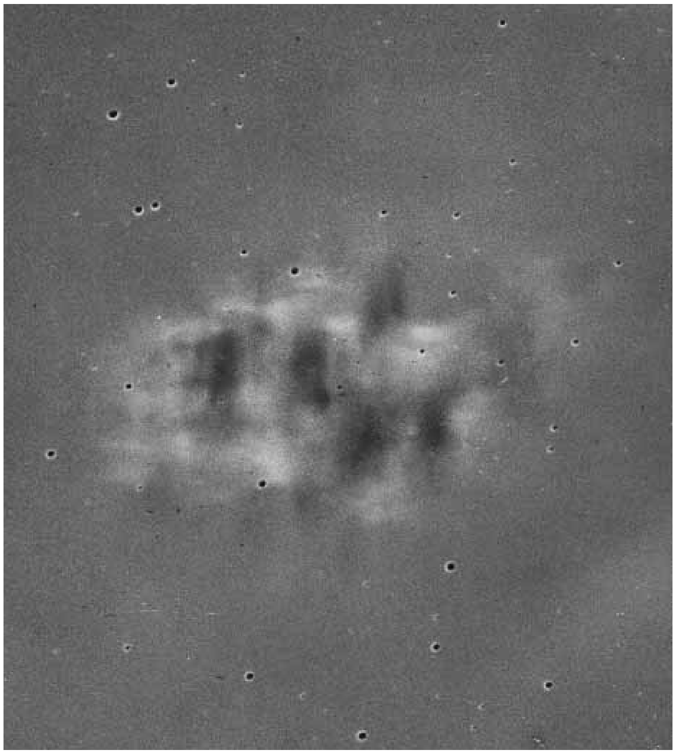
Left: Magnetic field vectors of the face-on spiral galaxy M51, from a 2.8 cm image obtained by Nikolaus Neininger. Clearly the field lines track the spiral arms at least approximately. (Copyright Max Planck Institute fuer Radioastronomie, Bonn, Germany; provided by Rainer Beck.) Right: Magnetic field vectors of the edge-on spiral galaxy NGC 4631, 6 cm image obtained by Goetz Golla and Ko Hummel. At least some spiral galaxies clearly also have a component of magnetic field extending more or less perpendicularly out of the disk. (Copyright Max Planck Institute fuer Radioastronomie, Bonn, Germany; provided by Rainer Beck.)

Information on magnetic fields in other types of galaxies is still sparser. The Large Magellanic Cloud, a sort of irregular galaxy and our nearest neighbor, has some coherent field, seemingly associated with star formation regions. As for ellipticals, a recent four-day conference on them doesn't even have magnetic fields as an index item in its proceedings. But a subset of giant ellipticals are the hosts of quasars and other strong radio sources, for which all models invoke significant fields, right on up to the (non-conventional) Strong Magnetic Field Model.

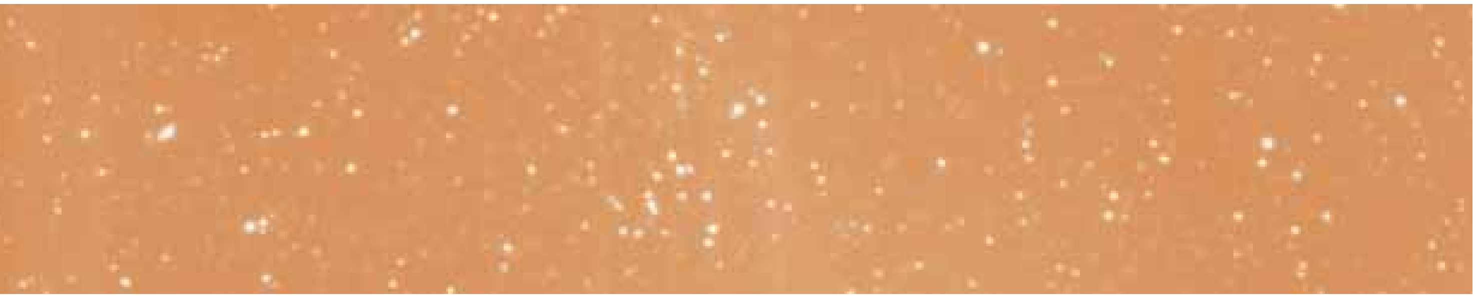
Galactic, at least spiral, magnetic fields have long been attributed to dynamos that derive their energy both from differential rotation and from gas turbulence (in turn driven by expanding supernova remnants and stellar wind bubbles). One set of theorists says that they can produce both axi- and bisymmetric spirals this way (though sometimes with another, unwanted, reversal of field direction across the galactic midplane). Another set periodically says that you get the wrong geometry, all the field energy cascades down to small length scales too fast, and that the saturation field is less than the real one . . . followed by rebuttals from the first set. Relevant observations are thin on the ground, but it does seem to be true that many galaxies at redshifts near two (when the universe was nine times its present density) already have fields as large as ours. This might be taken as a mild argument against dynamos, which take a while to get going. Alternatives to a dynamo are (1) "primordial fields," meaning you shove the problem back to a time whose physics is not easily probed in the laboratory or (2) smoothing out of localized fields originally contributed by supernovae.

SUPERNOVA REMNANTS

Yes, Virginia says that the radio, visible, and X-ray photons from the Crab Nebula are all synchrotron emission. They are polarized, have the right (power law) spectra, and whatever else you want. There is a patch of coherent field near the pulsar of nearly a milliGauss, and regions of 10-4-5 G further out, with field lines vaguely



*Polarization structure of the optical synchrotron emission from the Crab Nebula. Images of this sort were first created by Fritz Zwicky. This particular one consists of two photographs, taken at about the same time, through Polaroid filters. One photo had the Polaroid oriented in position angle 45 degrees (vertical in the reproduction), the other in PA 135 degrees (horizontal in the reproduction), corresponding roughly to the major and minor axes of the elliptical silhouette of the nebula on the plane of the sky. A positive transparency was then created from one of the glass negatives, and prints made of light simultaneously shining through the positive and the other negative. Thus polarized regions look lighter or darker than the sky average (and stars do not perfectly cancel out). Polarized regions are patchy and tend to have substructure roughly parallel to the polarization angle. This image is the inverse of one Zwicky published in 1956 (*PASP 68, 121*). Curiously, it is also a mirror image, representing the sky as seen from outside. A number of Zwicky's images of the Crab Nebula came to me at his death in 1974, and one can reasonably suppose that this one is reproduced with his permission.*



aligned with filaments of densish gas and perpendicular to the remnant edge. This centrally-condensed field is surely a gift of the pulsar, and some other, less famous, remnants look similar.

Synchrotron radio (but not optical or X-ray) emission is common to all known supernova remnants—not remarkable, since this is how we distinguish them from other kinds of hot interstellar gas clouds that emit radio bremsstrahlung. In most SNRs, however, the field lines run around the perimeter, not radially through it. We think this means that the field is mostly just swept up interstellar stuff.

One way or another, supernovae and their remnants are important to the galactic magnetic field. They may be the source of the "alpha" (turbulence) half of an alpha-omega dynamo (omega is the rotational part). They surely carry field into the halo. Perhaps they are even the ultimate source. This last is attractive largely because stellar dynamos are easier to model than galactic ones—not quite the same as their being closer to reality, of course. So, why not make fields in stars, concentrate them in pulsars, blow them out in pulsar winds that feed Crab-like remnants, and let the remnants expand and merge. Eventually there will be a good deal of random field out there that can be twirled around into the right pattern by galactic rotation and concentrated into the nucleus and into dense clouds by gas flows. This idea has gone in and out of fashion several time since 1968, and I am not sure what the current phase is.

Planetary nebulae, the expelled gaseous envelopes of lower mass stars than the ones that make supernovae, do not have detectable fields, though of course someone once (1962) said that they should.

RADIO GALAXIES AND QUASARS

The third extragalactic radio source identification was that of Cygnus A, meaning the brightest radio source in the direction of that constellation. Walter Baade and Rudolph Minkowski were able to get the critical picture in 1954 because radio astronomy had provided an accurate position, and the information that the radio photons were coming from two separate roundish bits of sky. The optical fuzz was in between the radio lobes and looked to Baade and Minkowski like two, flattened elliptical galaxies, colliding face to face. The modern interpretation is a single giant elliptical galaxy with a dust lane down its middle. Statistical evidence says, however, that interactions and mergers between galaxies do promote development of radio emission and other nuclear activity.

The early 1960s saw the discovery of polarization in radio galaxies and the discovery of the first quasars. These are, probably, also elliptical galaxies, but with nuclei so bright in visible light that the rest of the galaxy is nearly lost in the glare. Their radio emission is also linearly polarized, power-law-spectrum synchrotron. A much larger class of quasi-stellar objects (and also of less overwhelming active nuclei living in spiral galaxies and named for Carl Seyfert) are radio quiet, but bright in visible light and X-rays. Evidence for strong magnetic fields in them is less direct, and I will ignore them henceforth.

We have an official paradigm* for active galaxies. A central black hole of 10^{6-9} solar masses is accreting material from its surroundings, probably via a disk. The disk collimates jets of relativistic, magnetized plasma, which squirt out at high speed perpendicular to the disk, radiating as they go, and feeding energy out into large double lobes like those of Cygnus A. The jets and blobs are all more or less lined up from scales of a parsec near the black hole (resolved with very long baseline radio interferometry) to hundreds of kiloparsecs (a minute of arc on the sky, about the resolution of your eyes). One jet is bound to be pointing more or less toward us, the other away. Bulk relativistic motions thus make the approaching one look much brighter and result in structure changes observable from year to year.

**Within living memory, practicing scientists (won't we ever learn how?) used "paradigm" the way Kuhn had meant it, to mean an experiment that set an example for the way things ought to be done. Its current usage comes closer to the "best buy model" of* Consumer Reports.

Traditional calculations presume that the energy in relativistic electrons plus magnetic field ought to be the minimum to produce a given flux of synchrotron radiation. You get almost exactly the same numbers by assuming equal energy density in particles and field—yet another case where one mumbles to oneself "coincidence/obvious/causal/remarkable . . ." Extended radio blobs require a microGauss or two, compact bits more like a milliGauss. The equipartition field just outside the black hole horizon is about a Tesla, the only context I know in which this is a useful unit. Polarization studies show that lobe fields are fairly chaotic, while the core and jet ones are often sharply aligned with the jet axis.

Anyone bringing a fresh and vacant mind to the contemplation of quasars and their ilk will have some pretty pointed questions. For instance, if the extended lobes consist entirely of relativistic fluids—high speed electrons and magnetic field—why aren't they expanding at the speed of light perpendicular to the source axis? This is called the "radio source confinement problem." Various attempts to tie the field lines to some large, nonrelativistic mass are fairly unpersuasive. The winner seems to be ram pressure, that is, the confining effect of a tenuous medium through which jets and blobs propagate. The confining pressure is then $\rho_e v^2$, where ρ_e is the external gas density. It has to balance the outward, $B^2/8\pi$, pressure. A reasonable estimate of circumsource gas density leads to minimum speed of at least 10–30 percent of c. Bigger than c is unlikely. The range is the same as what we deduce from rapid central structure changes, and implies a fairly narrow range of possible lifetimes for the extended sources, near 10^8 years. This is also about the time it takes for a central black hole to double its mass given the rate stuff must fall in to keep up all the activity, and so is probably about right. It is left as an exercise for the reader to consider water skiing as a problem in ram pressure support and to calculate the minimum speed the tow boat must move to keep you from sinking.

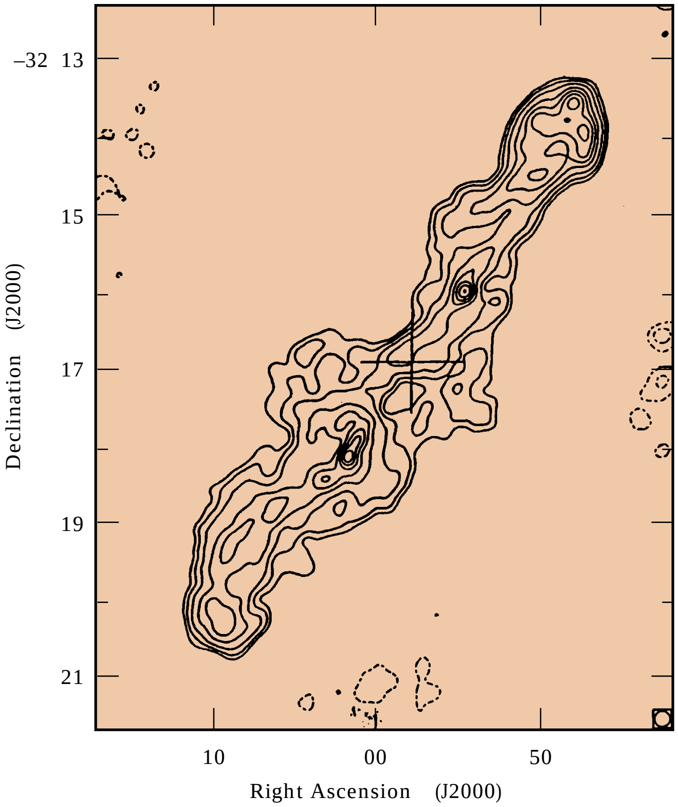
Next question: what and where are the currents that maintain these magnetic fields, or at least generate them initially? You can read a lot of quasar review articles without finding many sentences devoted to this issue. The fields must have originated outside he black holes, and the commonest assumption is that inflowing gas has always carried its field with it, to be amplified in a differentially rotating accretion disk and then partly dumped inward and partly shot back out in the jets, helping to collimate them in the process. Most recent models lean heavily on the "twin exhaust" ideas put forward in 1974 by Roger Blandford and Martin Rees, then both at Cambridge.

The twin exhaust and related models also provide some answer to what the jets are made of—probably relativistic electrons and positrons (in equal number to within $\pm 10^{-17}$ or so) plus field. An alternative idea, coming slightly earlier, also from Rees, had the jets starting out as pure low frequency electromagnetic waves from the central magnetized black hole (acting like a pulsar). Ambient, thermal electrons could ride the E vector waves, soon reaching relativistic speeds, and then perceive the B vector part as a nearly static magnetic field in which to spiral and emit synchrotron photons. This scenario falls afoul of detailed polarization data, but still seems to me to be very elegant.

JETS AND DISKS WHEREVER YOU LOOK

You have already been asked to believe in magnetized accretion disks and the jets they collimate as explanations for angular momentum removal and outflowing gas from young stars and for much of the phenomenology of active galaxies. Similar things happen other places as well, including the surroundings of neutron stars and black holes in X-ray emission binary star systems and in the binaries with a white dwarf that give rise to nova explosions. Two or three galactic X-ray sources have associated radio jets that move outward, like the quasar ones, at 25–75 percent of c, so that we see rapid structure changes and/or greatly redshifted and blueshifted optical emission lines.

Perhaps you won't be surprised, since you know that the underlying physics is much the same, that all these disk/jet objects look quite similar, whether the central



Contour diagram of a random, powerful radio source in the southern sky. Experienced radio astronomers claim that such diagrams are really more informative than ordinary halftone photographs, but they take a bit of practice to appreciate (I mean the pictures, not the radio astronomers.). Closely spaced contour lines mean that the surface brightness is changing rapidly with position there. The brightest bits are the ones most contour lines away from the edges. Some sources have their brightest bits at the tops of the lobes; others do not. Sources also vary considerably in their degree of asymmetry between the two sides (thought to be largely a relativistic beaming effect). Very similar configurations, on very different size scales, are associated with cores of some galaxies, X-ray emitting binary stars, and young stellar objects. (Courtesy Richard Hunstead, University of Sydney)

core is a young star, a stellar mass black hole, or a supermassive black hole. In fact, in plots of radio contours like the illustrationon above, even a fairly experienced astronomer will have to look at the angular scale of the image (or the name of the observer!) to be sure of whether he is contemplating a large double radio source, a compact core source, or a Herbig-Haro (young star) source. And for all these configurations, magnetic fields are dynamically and energetically important in a way they are not for planets and stars.

LONG AGO AND FAR AWAY

Magnetic fields pervade at least some clusters of galaxies. The evidence includes diffuse radio emission and Faraday rotation and depolarization of radio lobes belonging to galaxies in the clusters and sometimes also of radio sources behind the clusters. Field values are surprisingly high, not much smaller than galactic values. That is, one finds 1–10 μG near large, central galaxies and tenths of microGauss further out in the clusters.

I can think of only three possible classes of explanation, and all have been defended within the present decade. First, these are fields originally belonging to normal and active galaxies, shot out with winds and jets. Second they are generated in situ by dynamos in hot intracluster gas (which is certainly there—we see the X-ray emission). Third, it is primordial magnetic field, brought into dark matter halos by the gas that flowed into form the cluster, later amplified by gas turbulence.

"Primordial" in this context essentially means "attributable to processes before galaxies formed." As far as I am concerned, it also means "attributable to processes I don't understand." Recent suggestions have included vorticity in the early universe and the inflationary epoch invoked for other reasons, and, perforce, I stop here, finding, as Ehrenfest said, that it is quite difficult to explain something even if you understand it, and almost impossible if you don't. There is a well-known Wittgenstein quote that would be equally apposite here, but it never seems to come out very well in English (perhaps because there is no way to put the "daruf" at the end?), and so you must supply it or some equivalent for yourself.

STILL MORE WORDS

THE CLASSIC TEXT is Ya. B. Zeldovich, A. A. Ruzmaikin, and D. D. Sokoloff, **Magnetic Fields in Astrophysics**, Gordon & Breach (New York) 1983.

Two relevant symposia of the International Astronomical Union are published as: R. Beck, P. Kronberg, and R. Wielebinski, Eds., **Galactic and Inter-Galactic Magnetic Fields**, Kluwer, 1990.

F. Krause, K.-H. Raedler, and G. Ruediger, Eds, **The Cosmic Dynamo**, Kluwer, 1993.

The era of magnetically dominated spirals and the galactic radio halo is represented in articles by L. Woltjer (p. 531) and J.L. Pawsey (p. 219) in A. Blaauw & M. Schmidt, Eds., **Galactic Structure**, U. Chicago Press, 1965.

Readers who cultivate the truly arcane might be interested in: *The Strong Magnetic Field Model* which appears most recently as H. D. Greyber, p. 298, of V. Trimble & A. Reisenegger, Eds., **Clusters, Lensing and the Future of the Universe**, Astronomical Society of the Pacific Conference Series No. 88, 1996 (and references therein).

The very first appearance of “a new model for extragalactic radio sources” in the form of a meeting abstract, M. J. Rees & V. Trimble, BAAS **3**, 25 (1971). This is probably the most important paper on which my name has ever appeared, and, sadly, I was merely the introducer, required by Society rules for papers by non-members.

A sharp-eyed colleague (Joe Tenn of Sonoma State University) found the missing Soul of Lodestone, author Alfred Still (1869–?), released in a late, 1946, edition by Murray Hill Books (New York and Toronto).

R. Kulsrud et al,. 1996, *Physics Reports* (in press) provide an up-to-the-minute overview of the pros and cons of large-scale dynamos and primordial magnetic fields.